

Thermal Imaging for Inspection of Large Cryogenic Tanks

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Abstract

The end of the Shuttle Program provides an opportunity to evaluate and possibly refurbish launch support infrastructure at the Kennedy Space Center in support of future launch vehicles. One major infrastructure element needing attention is the cryogenic fuel and oxidizer system and specifically the cryogenic fuel ground storage tanks located at Launch Complex 39. These tanks were constructed in 1965 and served both the Apollo and Shuttle Programs and will be used to support future launch programs. However, they have received only external inspection and minimal refurbishment over the years as there were no operational issues that warranted the significant time and schedule disruption required to drain and refurbish the tanks while the launch programs were ongoing. Now, during the break between programs, the health of the tanks is being evaluated and refurbishment is being performed as necessary to maintain their fitness for future launch programs. Thermography was used as one part of the inspection and analysis of the tanks. This paper will describe the conclusions derived from the thermal images to evaluate anomalous regions in the tanks, confirm structural integrity of components within the annular region, and evaluate the effectiveness of thermal imaging to detect large insulation voids in tanks prior to filling with cryogenic fluid. The use of thermal imaging as a tool to inspect unfilled tanks will be important if the construction of additional storage tanks is required to fuel new launch vehicles.

Keywords

Cryogenic Storage Tanks, Thermography, Thermal Imaging, Insulation

Introduction

Two 850,000 gallon cryogenic liquid hydrogen and two 900,000 gallon cryogenic liquid oxygen storage tanks were constructed by Chicago Bridge and Iron in 1965 at Kennedy Space Center's Launch Complex 39 Pads A and B to support the Apollo/Saturn V Program (TM-479, 1968). These tanks are composed of a stainless steel inner sphere, which carries the cryogenic liquid, hanging inside of a carbon steel outer sphere as shown in Figure 1. The region between the two spheres, i.e. the annular region, is filled with perlite, a powder insulation whose primary purpose is to minimize heat transfer via blackbody radiation between the two concentric spheres. The outer sphere is primed and painted to minimize corrosion, a serious problem due to the proximity of the Atlantic Ocean, Figure 1. These tanks supported both the Apollo and Shuttle programs yet received minimal refurbishment and only external inspection over their many years of service. One reason for this lack was that the manufacturer indicated that after a few temperature cycles, one of which would be required to warm the tank to permit an internal inspection, that the perlite may begin to compact, affecting the tank's performance. Consequently, during the entire Shuttle program (1981 onward) care was taken to maintain liquid oxygen or hydrogen inside of the tanks, minimizing thermal cycling.

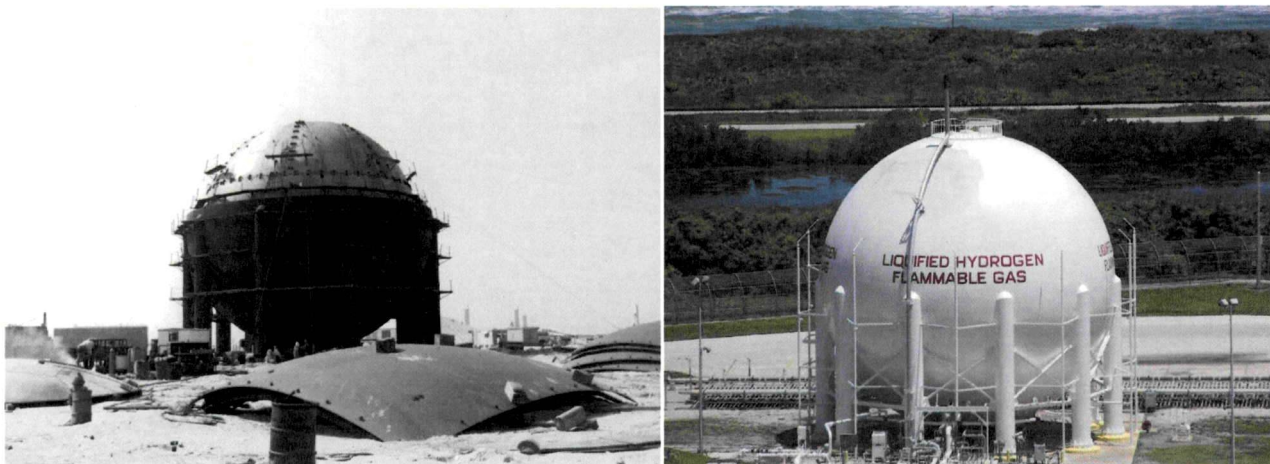


Figure 1. The left image shows the Pad B LH2 tank during construction showing the inner stainless steel sphere sitting within the partially completed outer carbon steel shell. The right image shows the completed, painted, tank during the 1990s as seen from the launch pad. The ocean is just beyond the dunes in the background.

Insulation Anomalies

Thermal imaging was performed on the liquid hydrogen and oxygen tanks while cryogenic fluid was present to identify major anomalous areas that may be visible due to temperature differences between the inner and outer shells of the tanks. These images indicated that there were large regions in two out of the four tanks, the Pad B hydrogen tank and the Pad A oxygen tank, where there was increased heat transfer between the inner and outer shells. This heat leakage, though covering a large area in both tanks, caused more of a deviation from expected performance for the hydrogen tank because of tank design and differences in the density and heat of vaporization of the two fluids. It takes approximately 7.7 times the energy to transition oxygen from liquid to gas as it does an equal volume of hydrogen so an equal amount of heat leakage into the tanks will boil off more hydrogen than oxygen (Flynn, 1997). Tank design also plays a role in the significance of the heat leak because the annular region in the oxygen tanks are back filled with nitrogen whereas the hydrogen tank annular region is held under vacuum so that the hydrogen tanks have better insulating properties overall. Because the oxygen tank design allows for a higher rate of heat penetration into the inner vessel under nominal conditions, an increase in liquid loss rate due to under insulated regions would not cause as significant of a deviation from the nominal tank performance as it does in the hydrogen tanks.

Figure 2 shows anomalous regions located near the top of the Pad B hydrogen tank (left) and the Pad A oxygen tank (right). The temperature variation on the surface of the hydrogen tank shows a large cooler region (darker) near the top of the tank with a few lighter regions (warmer) in the center. These warmer regions in the center of the large cooler region are due to the solar heating of dark mold growing on the surface of the tank (see figure 3). The mold on the tank surface was caused by the year round prevalence of condensation in this region and was the primary indicator of the location of the thermal issue with the tank. The mold does provide a visual indication of the main area of heat leakage; however, as indicated by the thermal images, the true anomalous region extends beyond the area of mold growth alone.

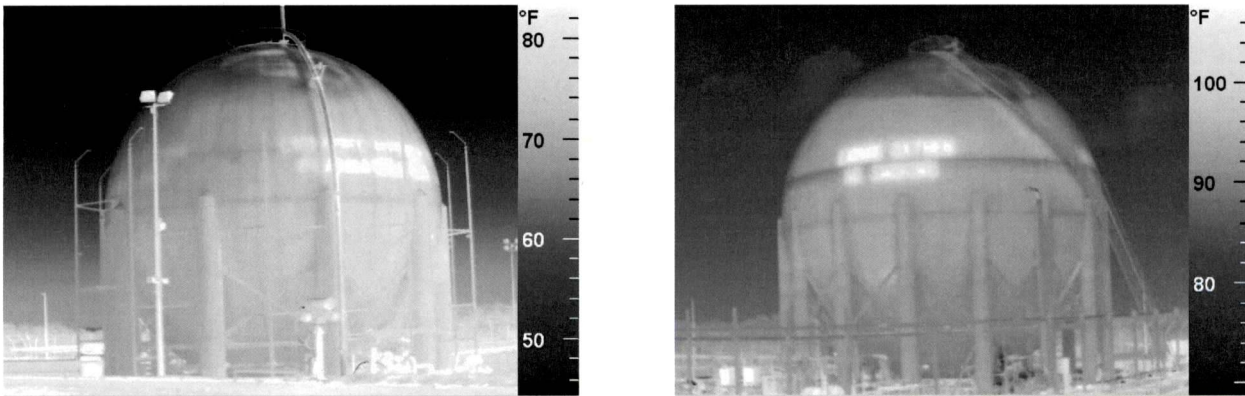


Figure 2: (left) Thermal images of the Pad B liquid hydrogen tank and (right) Pad A liquid oxygen tank showing areas of heat leakage near the tops of the tanks.

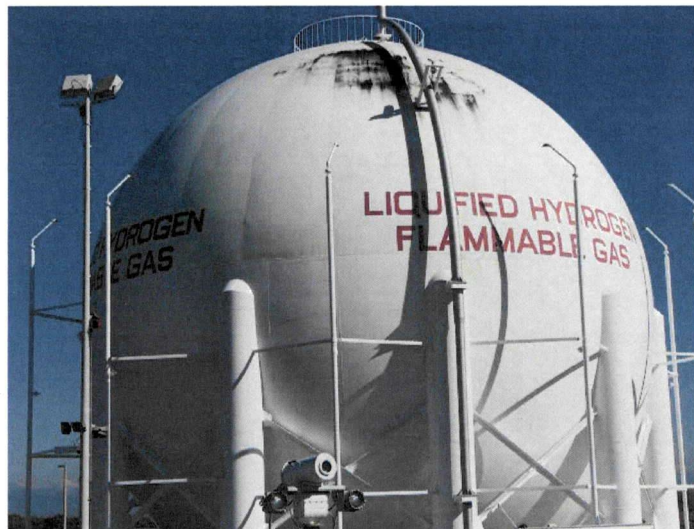


Figure 3: This image shows the mold on the top of the Pad B liquid hydrogen tank, resulting from the condensation of moisture onto this cold region of the tank.

The effect of the additional heat leakage into the storage tanks can be found from the historical measurements of tank levels by determining the average number of gallons of liquid lost per day. Though all the tanks supported the launches adequately throughout the programs, the LC-39 Pad B hydrogen tank's thermal performance was never within the original specifications (75M14524, 1965), and the loss rate of hydrogen was significantly higher than that of the similarly constructed tank on Pad A. The hydrogen and oxygen loss rates in the figures 4 and 5 were calculated from available historical tank level measurements during calm periods where there were no launch attempts or operations that would disturb the liquid level in the tank for at least 1 month. The data shows that the additional heat transfer into the oxygen tank did not significantly increase the loss rate of the Pad A tank compared with the Pad B oxygen tank. However, the additional heat transfer into the Pad B hydrogen tank did significantly increase the loss rate of hydrogen as compared to the Pad A tank which had no anomalous areas of heat

penetration. The data for the Pad B hydrogen tank indicates that the thermal problem likely existed since the tank was initially constructed though may have grown a little worse over time.

Analysis was performed in 2003 to estimate the heat flow into the tanks after a spike in the loss rate was observed during sandblasting/painting. The analysis indicated that the heat leak into the inner vessel was likely due to an insulation void. Based on the size estimates of the cold spot from the thermal images, mathematical models were later refined to further validate radiative heat transfer due to an insulation void as the likely cause for the additional boil-off seen in the Pad B LH2 tank.

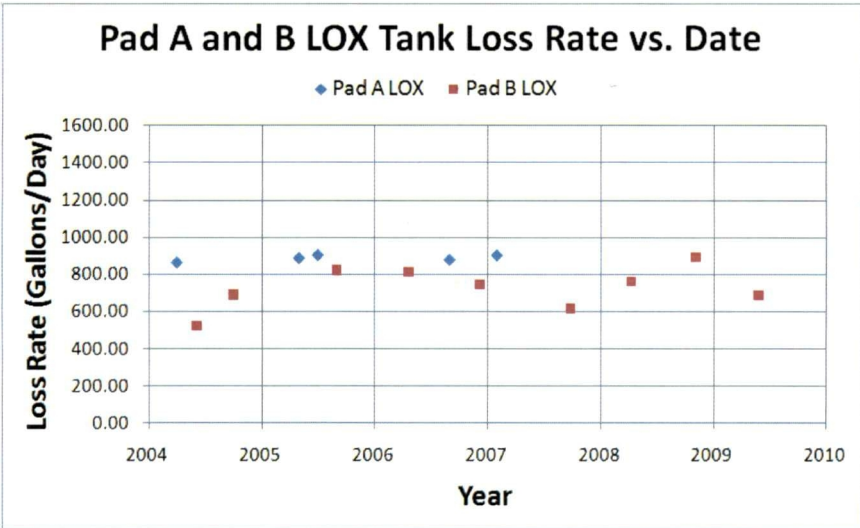


Figure 4. The daily loss of liquid oxygen in the LOX tanks at Pads A and B. Note that even though thermography showed a heat leak in the Pad A tank it had little effect on the thermal performance.

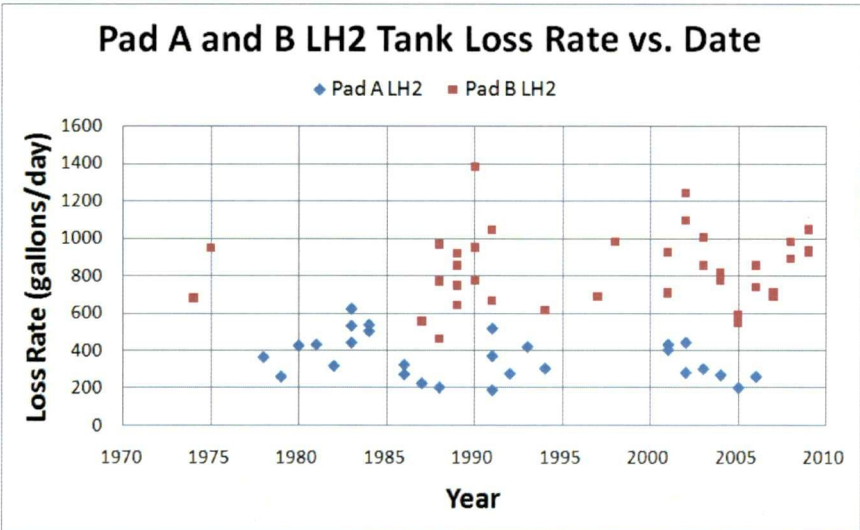


Figure 5. The daily loss of liquid hydrogen in the LH2 tanks at Pads A and B. In this case the additional heat leak in the Pad B tank resulted in significantly poorer thermal performance than the Pad A tank.

Structural Anomalies

Pad B refurbishment processes began in 2007 to ready the pad to support future launch programs. In support of the decision making process on the extent of the refurbishments that would be required for the cryogenic storage tanks, thermal imaging was performed to look for any structural anomalies in the tanks. Using the sun as the heat source underlying structural components that were welded to the outer sphere could be identified as they took significantly longer to warm and come into equilibrium with the surrounding outer shell steel. All tie rods, the structural elements that connect the hydrogen carrying inner shell to the outer shell, were identified in this way. Also visible the thermal images are longitudinal stiffener beams and horizontal girders. Besides ensuring that there were no structural anomalies the locations of the components were compared to design drawings to help determine the extent the insulation void on the Pad B hydrogen tank. The extent of the insulation void as estimated from the thermal images correlated well with visual inspections of the annular region that were made after the tank had been fully drained and warmed to ambient conditions.

Monitoring Tank Warm-up

The combined issues of poor thermal performance and necessary structural maintenance led to the decision to drain the Pad B hydrogen tank, warm it to ambient conditions, and release the vacuum in the annular region. Thermal imaging was performed during the drain process to monitor the tank for any changes in the size of the anomalous region and determine the minimum temperature difference needed between inner and outer shells of the tank to be able to detect anomalous regions. An indication of the cold region persisted through the drain process to the point where the inner tank was warmed to ambient conditions. The images below are from when the tank still contained hydrogen, when the inner tank was approximately six degrees Fahrenheit, and after the tank has been fully warmed. There was no access to directly measure the inner tank temperature so estimates were based on the temperature of the helium purge gas that exited the inner tank.

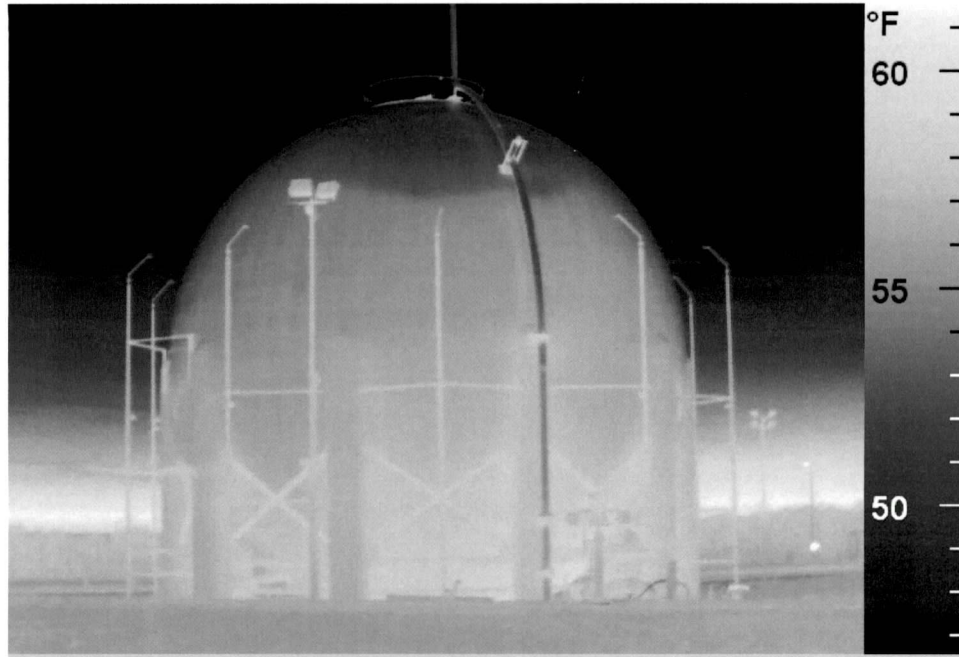


Figure 6. The image was taken on March 9, 2010 with a Jenoptik VarioCam LWIR camera. The inner tank temperature was approximately 6°F and annulus pressure was 3.5 PSIA. Overcast skies provided for good imaging as the moldy area did not absorb heat as readily as with direct sunlight and therefore did not mask the visibility of the cold spot.

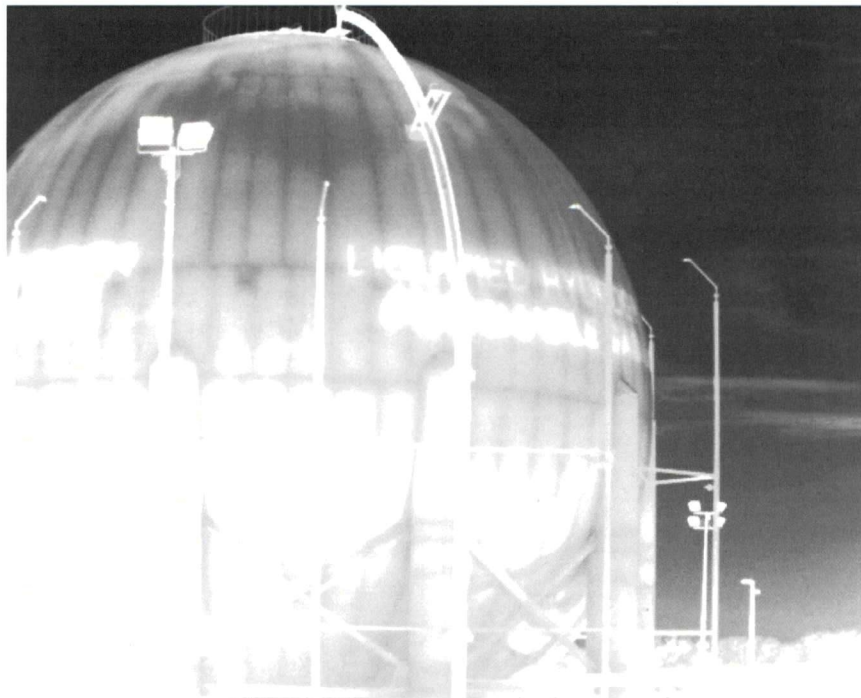


Figure 7. This image was taken on 6/29/2010 at 11:40 AM with a Titanium 560 MWIR camera. The inner vessel temperature is near ambient temperatures and the annular region pressure is at one atmosphere. A cold area indication can still be seen to the left of the vent line though it is not as apparent as when the inner tank is chilled.

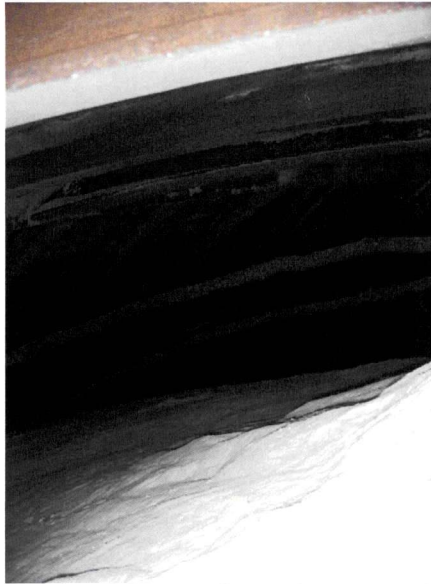


Figure 8. After the tank had been warmed and the annular region pressurized to one atmosphere a boroscope was used to inspect the cold spot from the inside. It was seen, as predicted by the thermal imaging and modeling, that insulation was missing from this region. Additional perlite was brought in and used to fill this void, so hopefully the Pad B LH2 tank will perform to the same level as the Pad A tank.

Prefill Insulation Void Detection

One of the objectives of the thermal monitoring during the drain process was to determine the feasibility of using thermal imaging as a tool to detect insulation voids in unfilled cryogenic tanks where the temperature difference between the inner and outer shells of the tank would only be a few degrees. To compliment the field imaging, a mathematical analysis was performed on a simplified tank model to determine the feasibility of detecting surface temperature differences between a location with an underlying void and the surrounding area. The model considered conductive, convective, and radiative heat transfer between the steel shells as well as the heat transfer between the outer steel shell and the environment. Many assumptions were made in this analysis because direct temperature measurements and the true values for the surface emissivity of inner tank surfaces had to be estimated. The analysis, using idealized environmental conditions for the modes of external heat transfer and assuming the inner and outer shell temperatures were initially in equilibrium, showed that it would be reasonable to expect a surface temperature variation of a few degrees Fahrenheit between surface regions over a void location and the surrounding normally filled areas. Temperature gradients of this size would be easily detectable with current infrared cameras and detectability maybe further enhanced if time series images are taken to monitor the rate of temperature change over the surface.

The surface temperature variation would develop because of the environmental temperature cycle from day to night as well as the large thermal mass of the inner and outer spheres of the tanks. The temperature cycling of the inner tank would lag behind the temperature cycling of the outer shell of the tank as heat is transferred between the two. For the emissivities that were assumed in this analysis, radiative coupling between the inner and outer shells of the tank in an area with an insulation void would increase the heat transfer between the shells in comparison to a region with normal insulation. A detectable temperature variation over the surface of the outer tank shell would develop between the void region and surrounding areas with normally filled insulation. For the case of the KSC tanks, the outer shell was 11/16th inch thick carbon steel and the inner steel shell is 1.16 inch thick stainless steel (TM-

479, 1965) providing a large thermal mass so that the heat transfer between surfaces to equalize temperatures would be relatively slow. The results of the simplified model are shown in Figure 12. The input parameters used in the model, especially the values used to estimate the heat transfer to the surrounding environment, can vary significantly and so the results are not reliable for all situations but demonstrate that the temperature difference is feasible under idealized conditions.

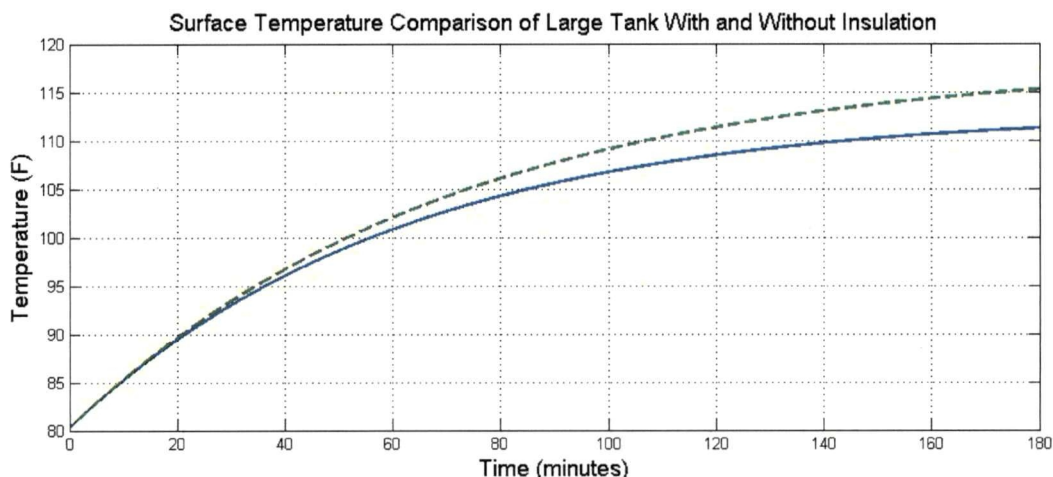


Figure 9. This plot shows the temperature of the outside steel shell for a large cryogenic tank as it is heated in the sun. The two plots correspond to the presence and absence of perlite insulation between the outer and inner shells. Without the insulation the outer shell transfers heat to the inner shell and heats more slowly. Consequently, areas of missing perlite may be detected using thermal imaging before filling the tank with cryogenic commodity.

Summary

Thermal imaging was demonstrated as an effective tool for identifying areas of heat penetration in active cryogenic tanks as well as locating underlying structural elements. The thermal images taken during the liquid hydrogen tank drain process and simplified mathematical model show that thermal imaging can be used to detect insulation voids of the size that existed in the LC-39 Pad B hydrogen tank. Depending on the tank geometry, surface emissivity and material thicknesses, thermal imaging may be a viable tool for acceptance testing of new or refurbished tanks before cryogen is introduced, though a mathematical analysis should be performed based on specific tank configurations and materials for each situation under consideration. Effective use of this tool for early identification of insulation voids has the potential to save significant time and reduce cost if corrective actions can be taken before cryogen is introduced into the system.

References

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